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THE INSTITUTION OF PRODUCTION ENGINEERS

Research Department.

THE NATURAL SAG OF TEST MANDRELS AND ITS CONSIDERATION IN CHECKING MACHINE TOOLS

By Dr. Geo. Schlesinger, Director.

THE most widely used inspection tool in the manufacturing and accepting of new machine tools, and the repairing of old ones is the test mandrel, the quality of which (i.e. for straightness and roundness) is of paramount importance for accurate results. But a further factor is often overlooked—the " natural sag " or deflection due to the mandrel's own weight, which occurs when the mandrel is fixed between centres and, more markedly, when it is supported only by the taper shank at one end, with the outer end hanging freely.

The Research Department has investigated the influence of the natural sag of test mandrels used to check alignments of machine tools. This sag is frequently not taken into consideration and causes trouble and discussion which can be avoided, when the

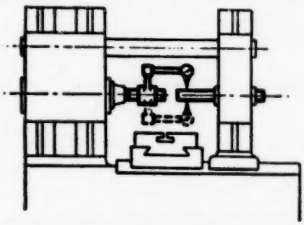


Fig. 1.—Alignment test of axis to axis by turn-round method.

characteristics of solid and hollow mandrels are known and used in the interpretation of alignment tests, of which " axis to axis " (Fig. 1) and " axis to plane " (Fig. 2) are the most frequent examples.

To find rules which could be commonly accepted the following three taper shanked mandrels were inspected:—

(1) A solid mandrel, 1 in. diameter and 12 in. long.
(2) A solid mandrel, $2\frac{1}{2}$ in. diameter and $21\frac{3}{4}$ in. long.
(3) A hollow mandrel of the same external dimensions as (2).

The shanks of Nos. (2) and (3) were Morse No. 5 taper (I.S.A. standard), while that of (1) had a " Norton " taper.

The following results were obtained :—

No. 1.—The small mandrel was first tested in V-blocks on a carefully levelled surface plate (Fig. 3). The measuring instrument used was a dial gauge reading to 0.0001 in. per division, with a linear calibration curve (Fig. 4). The nominal tolerance for readings was one of ± 0.2 divisions (i.e., ± 0.00002), but it was found in practice that it could hardly be relied on to anything better than half division $= \pm 0.00005$ in. During all the readings the plunger was displaced from its position of rest by an amount corresponding

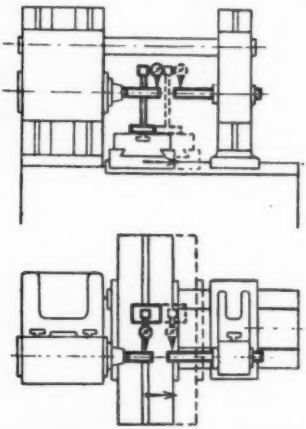


Fig. 2.—Alignment test axis to plane, moving the dial gauge.

to approximately three revolutions of the pointer (0.03 in.), and the plunger pressure was about 3 oz. It was found that (*a*) the cylindrical portion of the mandrel was accurate within 0.0001 in. at any point ; (*b*) no " out of round " could be detected ; (*c*) the top surface of the mandrel was dead level (i.e., no variation in the height above the surface plate could be detected with the dial gauge).

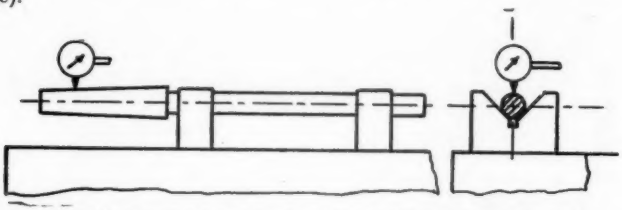


Fig. 3. Checking the taper shank mandrel in V-blocks. Truth of cylinder and taper.

The taper portion showed a maximum deviation of three divisions, 0.0003 in. on its full length. This error was such as to cause an inclination α (Fig. 5) between the centre line of the taper portion and that of the cylindrical portion. The taper itself was dead round at all positions along the length. Consequently the mandrel itself was fairly good.

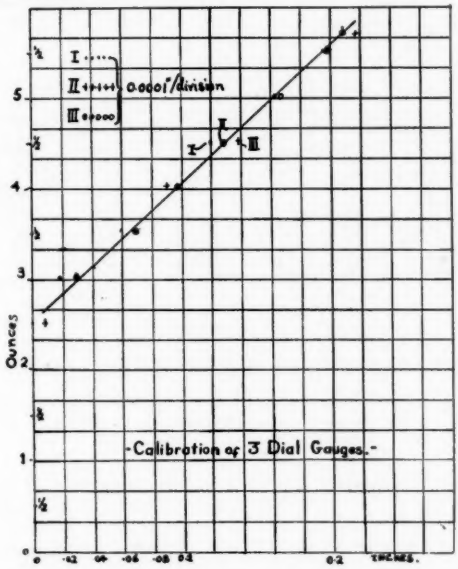


Fig. 4.—Straight line calibration curve of three good British dial gauges.

To find the sag, a ground bushing* with taper bore and outside diameter of about 2.9364 in. at *A* and *B* was used as a main bearing (Fig. 6). The internal taper was finished so as to mate accurately

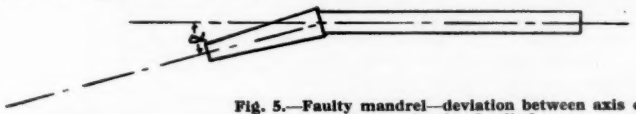


Fig. 5.—Faulty mandrel—deviation between axis of taper and axis of cylinder.

with that of the mandrel. The bushing itself was inspected in vees, V_1, V_2, placed on the surface plate. The external cylinders

* The extraordinarily well made bushing and the small mandrel No. 1 were presented by the Austin Motor Co., Ltd., Birmingham.

at A and B were slowly turned and showed deviations from the round of about half a division (=0.00006 in.). The internal diameters were measured at C and D at the same time as those at A and B. Axial movement was prevented by giving the bushing constant axial pressure against a rigid stop S. Both readings indicated dead round (i.e., any variation was not measurable with the dial gauge used). The concentricity of taper bore and outside

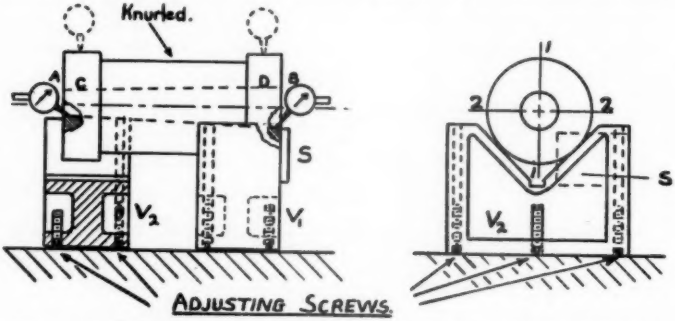


Fig. 6.—Cylindrical bushing with taper hole, checked on adjustable V-blocks.

cylinders A and B was checked by a Newall measuring machine and found to be exact; the diameters at A and B were also measured with the following results—

A =2.93644 (diameter 1—1)	B=2.93644 (diameter 1—1)
=2.93650 („ 2—2)	=2.93654 („ 2—2)
0.00006 out of round	0.00010 out of round.

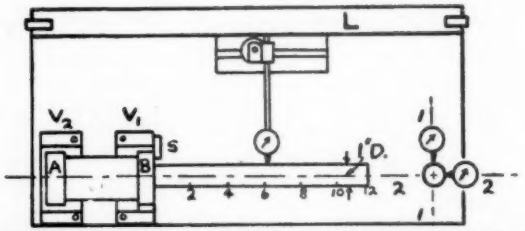


Fig. 7.—Testing the position of the measuring cylinder against the surface plate, vertically and horizontally. Theoretical axis parallel to surface plate.

This bushing was used as bearing for the taper shanked cylindrical mandrel, supported by cast-iron vees, the height and inclination of of which could be adjusted by three fine screws (Fig. 6). This was

necessary to get the theoretical axis of the mandrel parallel to the surface plate. To this surface plate a hardened and ground straight-edge L, was clamped, as reference line for the horizontal adjustment of the mandrel (Fig. 7). To this straight-edge the vertical direction plane of the stand for the dial gauge was pressed, so that the straight-edge was the vertical reference plane, and the surface plate was the horizontal reference plane, for all measurements. The

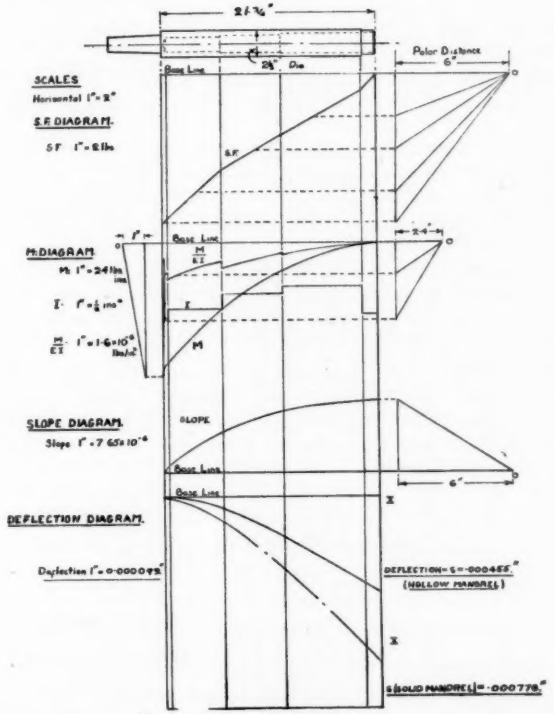


Fig. 8.—Graph to determine the Natural Sag of Solid and Hollow Mandrels of the same Outside Dimensions

vee-blocks were clamped to the surface plate after their adjustment in both measuring planes was completed. The natural sag of the mandrel, 1 in. in diameter, 12 in. long, placed in the bushing could be calculated as a free hanging cantilever of constant diameter,

throughout the length, loaded by uniform weight. Max. deflection $= \frac{WL_3}{8\,EI}$ This calculation was made by the ordinary deflection formula for such a uniformly loaded, free cantilever and by graphical determination, using the Mohr theorem. The graphs were made according to Fig. 8 for the big mandrels of $2\frac{1}{2}$ in. dia. For the latter a base line $21\frac{3}{4}$ in. long was drawn and the maximum shear force calculated. The shear force is zero at the free end and increases uniformly to a maximum (= weight of free portion of cantilever) at the fixed end. This enabled the *shear force diagram* (S.F.) to be drawn (Fig. 8).

The base line was divided into suitable sections and the points, where the shear force graph cut the centre of each section, were found.

A suitable pole *O* was taken, for convenience at the right-hand side of the S.F. diagram (polar distance = 6 in.) on the base line produced. The points noted in the above paragraph were then projected across to cut the other axis of the polar diagram and joined up to the pole.

Now parallel to the lines in the polar diagram were drawn across the appropriate sections, starting at the free end and each line beginning, where the preceding one ended. The mid-points of these lines were joined up and were found to form a smooth curve.

Now, if a shear force diagram is integrated, we get a bending moment diagram (*M* diagram, polar distance = 2.4 in.). The process of drawing a polar diagram, etc., was merely a process of graphical integration. But in doing so a constant of integration was introduced, and thus it was necessary to find the position of the base line. As the bending moment (M.) at the free end of a cantilever is zero, the base line was drawn so that this condition was fulfilled.

In order to get the *slope diagram* (polar distance = 6 in.), it is necessary to integrate $\frac{\text{bending moment}}{\text{Ex moment of inertia}}$ diagram.

But since the moment of inertia was constant for each section, the $\frac{M}{ExI}$ diagram was the same as the M. diagram, measured on a different scale.

This diagram was integrated in the same way as the shear force diagram, but the base line occurred in a different position, since the slope was zero at the fixed end.

The *slope diagram was integrated* in the same way *to give the sag curve* (Fig. 8), and again the sag was zero at the fixed end, so the base line was fixed to fulfil this condition.

The sag or deflection was then found by scaling off the distance

XX and multiplying by the appropriate scale to get the result in inches :—

Scales—

M. scale = Length scale × S.F. scale × pole distance of S.F. diagram.

$\frac{\text{M.}}{\text{Ex.I}}$ scale = M. scale ÷ [I × E ; E = 30,000,000].

Slope scale = $\frac{\text{M.}}{\text{Ex.I}}$ scale × length scale × pole distance of M= diagram.

Sag scale = slope scale × length scale × pole distance of slope diagram (deflection diagram).

In the same way a solid mandrel of $2\frac{3}{4}$ in. dia. and $21\frac{3}{4}$ in. length is calculated (Fig. 8) (dash and dot line).

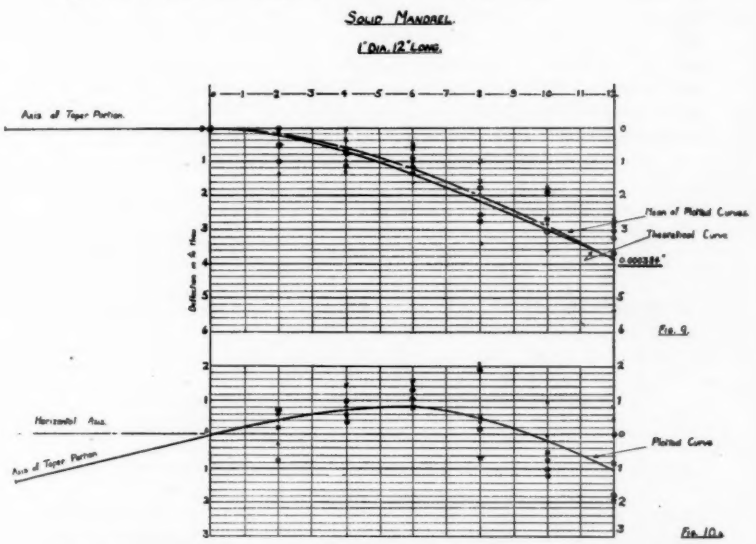


Fig. 9.—Comparison of practical deviations on the theoretical deflection parabola.

Fig. 10a.—Plotted curve. Deviation of axis of taper portion to horizontal axis.

The deflection was then worked out by direct calculation, and the same result for the 1 in. dia. × 12 in. long mandrel viz. 0.0003835 in. obtained. This parabolic deflection curve was now used to set up the real axis of the cylindrical part of the mandrel in the bushing on the surface plate. The adjusting screws were adjusted, so that

the mean difference in height between the fixed and free ends of the mandrel was approximately 0.000384 in. The required measurements were made in four positions of the mandrel, which was rotated 90° between each set of readings. To find the correct curve, the readings were made from 2 in. to 2 in. along the axis. The readings were made twice, first from the bushing to the free end, secondly from the free end to the bushing. The graph (Fig. 9) shows the deviations of all these points to the theoretical deflection parabola. The mean deviation curve is drawn with a chain dotted line. The maximum single deviations were ± 0.00013 in. The mean deviation was ± 0.000025 in. This mean deviation was within the limits of the dial gauge of 0.0001 in. division. The maximum real deviations were not more than one division. The coincidence of calculation and practical test is excellent. A cross-check was made by trying to adjust the axis of the mandrel distributing the natural sag (Fig. 10), equally above and below the horizontal axis. This could be done, because the V-blocks of the main bushing *A*—*B* (see Fig. 6) were adjustable. If the mean position of the axis of the cylindrical mandrel was to be approximately horizontal, the natural sag had to be distributed symmetrically $\pm$ above and below the theoretical horizontal axis. This has been really proved by the readings given

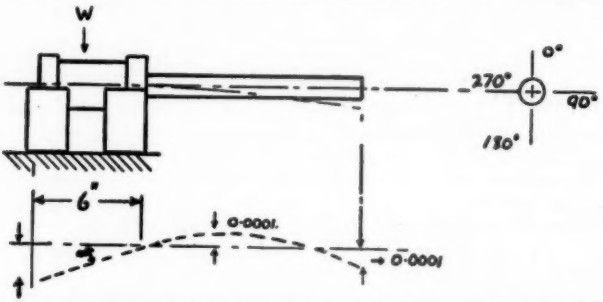


Fig. 10b.—Adjustment of axis of mandrel approximately parallel to surface plate.

in the four positions from 90° to 90°. They show in all cases that the sag prevents a full horizontal line, but the axis of rotation for the bushing *A*—*B*, which may represent for example the main bearing of a lathe or milling machine, was now inclined six divisions of the clock indicator (i.e., —0.0006 in.). This counter-check proves again that if the main spindle is horizontal, the sag of the mandrel is at least 0.000384 in. Generally it is much more, because accurate bearings and mandrels, such as were used, are generally not available. The bore of the spindle of an ordinary lathe must be true. The maximum permissible eccentric error is 0.001 in. to 12 in. length.

The same accuracy is required regarding the parallelism of the axis of the spindle with the bed, both in vertical and horizontal planes. For the tool-maker lathe the permissible error is only 0.0005 in. per foot against 0.000384 in. per foot sag. Further, the axis of rotation of the spindle given by the outside bearings *A*—*B* (Fig. 7) has often a deviation from the axis of the taper bore and, if the mandrel with errors is put to a spindle with errors and these errors are magnified by the natural sag, this deviation by sag must be taken into consideration and cannot be neglected, because it might be unfair to the maker of the machine.

The same mandrel was then loaded with a weight of 3 lb. (corresponding to the ordinary cast-iron bushing of a milling arbor) put on the mandrel at a distance of 8 in. from the front end of *B* (Fig. 11). The weight was $3\frac{1}{4}$ in. long=length of bushing, and the

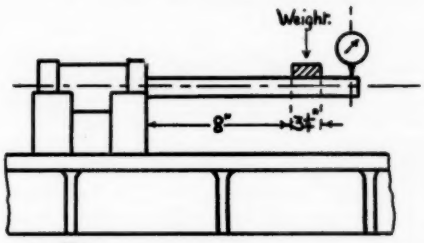


Fig. 11.—Influence of a load to the end of the mandrel (principle of slip bushing).

dial gauge used as comparator was set to the extreme end of the mandrel. The weight (of the bushing) on the sagging mandrel caused an added deflection of 0.0014 in. The total deflection is thus

$$\begin{aligned} &0.0014 \text{ in.} \\ &+0.000385 \text{ in.} \\ &\hline \\ &=0.001785 \text{ in.} \end{aligned}$$

This mandrel was in that case replacing a milling arbor of 1 in. diameter and 12 in. length, i.e., a very short arbor. The admissible error in testing the alignment of the bore of an arm bracket with the cutter spindles is 0.001 in. per foot. It is obvious that if the natural sag of the mandrel increased by the weight of the slip bushing is about 0.0018 in., it is difficult to measure the correct alignment by this method. The slip bushing method must, therefore, take into consideration the normal weight of the bushings which are used for the method of testing. Finally, the 3 lb. weight was replaced by one of 1 lb. 5 oz. corresponding to an aluminium alloy bushing, such as

might be used for checking mandrels. This caused a mean added deflection of 0.00065 in. giving a total sag of 0.001035 in. Thus if a light bushing of aluminium alloy or magnesium is used when checking overhanging arms by the slip bushing method, the effect of its weight, though considerably less than that of other types, is still not to be neglected even with short arbors. For long arbors weakened by grooves for the milling cutters, the result is quite unfavourable for the bushing method. These tests were also made on a Cincinnati horizontal milling machine with taper shanked arbor, $1\frac{1}{4}$ in. diameter, groove dimensions $^{3}/_{16}$ in. by $^{3}/_{32}$ in. by 20 in. long, with a cast-iron standard bushing, $2\frac{3}{4}$ in. diameter by 4 in. long, weighing 3 lb. 2 oz. (Fig. 12). The deflection due to the bushing (got by direct measurement of the sag with and without the bushing) was 0.0027 in. In such a case using the ordinary milling arbor and bushing the real deflections must be known and carefully taken

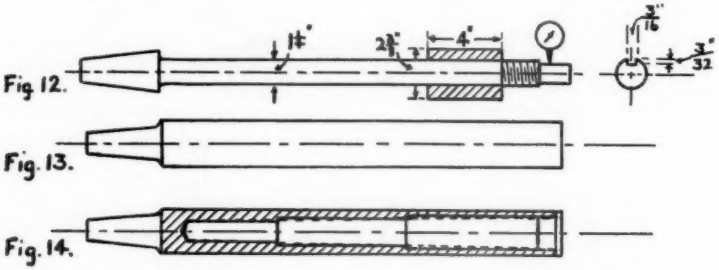


Fig. 12.—Practical example of slip bushing to milling arbor of 1¼ in. diameter.
Fig. 13.—Solid mandrel of 2½ in. diameter. (c.f. Fig. 8).
Fig. 14.—Hollow mandrel of the same dimensions. (c.f. Fig. 8).

into consideration, or else the measurement is wrong and the bracket is not aligned and may cause considerable heating of the front end of the arbor in actual work.

The standard (I.S.A. standards) *solid mandrel* of $2\frac{1}{2}$ in. diameter by $21\frac{3}{4}$ in. long had a No. 5 Morse taper, which is only 1.75 in. dia. at at the large end, i.e., smaller than the dia. $2\frac{1}{2}$ in. of the mandrel cylinder itself (Fig. 13). This is unsatisfactory from the point of view of deflection but these are the standardised dimensions. The design of mandrel No. 1 with the relatively large tapered portion is better.

The sag was calculated to be 0.00078 in., and was checked as correct by the graphical construction.

The standard (I.S.A.) *hollow mandrel* of $2\frac{1}{2}$ in. dia. by $21\frac{3}{4}$ in. (Fig. 14) of exactly the same dimensions as the corresponding solid mandrel above showed—(*a*) calculated sag = 0.000455 in. and (*b*) by the graph the same.

The construction of the deflection diagram (Fig. 8) is self-explanatory. The main difference from the solid mandrel diagram consists in the sudden changes caused by the internal stepped bore of the hollow mandrel.

The table shows the dimensions of the ordinary mandrels and their sag, solid and hollow (charged from sum to inches).

No.	Outside diameter	Inside diameter	Total length *L*	Length of measuring position	Calculated deflection at meas'g position	Remarks
	IN.	*IN.*	*IN.*	*IN.*	*IN.*	
1	$\frac{5}{8}$" = 0.625"	Solid	$5\frac{1}{4}$	$5\frac{1}{4}$	0.000,050	
2a	1"	Solid	$9\frac{1}{4}$	$9\frac{1}{4}$	0.000,167	
b	1"	$\frac{3}{4}$ in. bore	$9\frac{1}{4}$	$9\frac{1}{4}$	0.000,120	$\frac{1}{8}$ in. wall th'ghout.
c	1 in.	Solid	12	$11\frac{7}{8}$	0.000,384	
3a	$1\frac{1}{8}$"	Solid	$14\frac{1}{4}$	$13\frac{3}{4}$	0.000,314	
b	$1\frac{1}{8}$"	$1\frac{3}{8}$" bore	$14\frac{1}{4}$	$13\frac{3}{4}$	0.000,226	$\frac{1}{4}$" wall.
4a	$2\frac{1}{4}$"	Solid	$21\frac{3}{4}$	$20\frac{1}{4}$	0.000,776	See Figs.
b	$2\frac{1}{2}$"	parabolic stepped bore	$21\frac{3}{4}$	$20\frac{3}{4}$	0.000,455	8, 13, 14

Practical methods of eliminating the errors which may occur due to natural sag will now be described for testing the alignment of horizontal axes :—

(1) Swing-round method (Fig. 1 and Fig. 15).
(2) Double mandrel method (Fig. 2 and Figs. 16 and 17 a, b).
(3) Slip bushing method (Fig. 18 and 19).

(1) *Swing-round Method* (c.f. Fig. 1). This requires the use of a dial gauge (of any desired accuracy 0.001, 0.0005, 0.0001, etc.) and a mandrel (hollow) of any convenient size. Readings are taken 180° apart, so that half the difference between them gives the error between the two axes. The gauge, which should be of good quality, can be checked for back lash and accuracy of dial divisions by the use of slip gauges which are generally in the possession of the user. If the gauge is of the required accuracy, the accuracy of this method depends on the rigidity of the stand. In general, this has joints which are tightened up on a sliding fit by nut and screw. The stand elements are bars of various lengths and limited diameters, subject to change by the slightest touch or incorrect handling. Also any errors in the bearings of the main spindle will affect the readings. These are the principal objections to the use of a movable clock indicator, and are reasons for replacing the swing-round method by one employing stationary clock indicators and measuring from a fixed reference plane, i.e, the two-mandrel method (c.f. Fig. 2).

If, however, the stand on which the clock-indicator is fastened is practically rigid against deflection caused by the weight of the clock-indicator and the pressure of the spring which actuates the

feeler and by changing the position of the dial gauge during measuring, all these objections are eliminated and the method can compete with any other good existing method. Such a stand of a simple, cheap, but very effective design (tube, Fig. 15), has been devised by the Research Department and has been tested and found to give results with a 0.0001 in. dial gauge which are in the range of 0.00004 to 0.00007 and less error for 8 to 12 oz. weight of clock plus pressure of spring. These limits are permissible for all the swing-round method measurements, which may occur during the

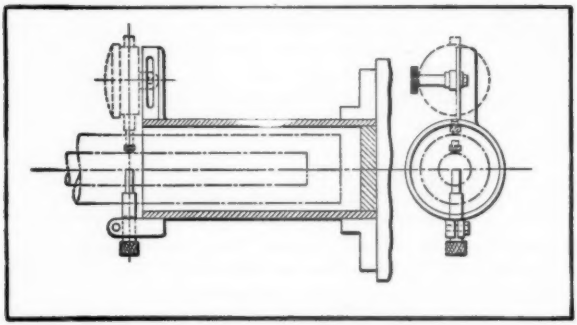


Fig. 15.—Tube stand for the swing-round method.

acceptance testing of machine tools, in particular for turret lathes, automatic screw machines, lathes, milling machines and grinding machines. The possible deflections were also calculated as follows :

Weight of tube alone=4.84 lb.
Outside diameter=3.5 in.
Inside diameter=3.19 in.
Hence moment of inertia I=2.283.
Length of tube=10 in.

Deflection of free end of tube due to own weight

$$=\frac{WL^3}{8EI}$$

$$=\frac{4.84\times10^3}{8\times30\times10^6\times2.283}$$

$$=0.00000883 \text{ in.}$$

Weight of supporting arms, etc., at outer end of tube=.92 lb.

Deflection due to above $=\frac{WL^3}{3EI}$

$$= \frac{.92 \times 10^3}{3 \times 30 \times 10^6 \times 2.283}$$

$$= 0.0000045 \text{ in.}$$

Total deflection of structure = .0000133 in.

Added deflection due to weight of clock plus plunger pressure = 8 oz.

is $\frac{WL^3}{3EI}$

$$= \frac{.5 \times 10^3}{3 \times 30 \times 10^6 \times 2.28}$$

$$= .0000024 \text{ in.}$$

ditto with weight of clock plus plunger pressure = 12 oz.

is $$\frac{.75 \times 10^3}{3 \times 30 \times 10^6 \times 2.28}$$

$$= .0000036 \text{ in.}$$

These last two figures are seen to be very much less (about $^1/_{20}$th) of the practical results, which would seem to show that the latter were principally due to the movement of the chuck, change in the bearing oil film, etc.

Calculation and practical test prove both that such a tube is extraordinarily rigid (c.f. report on "The Dial Guage and its Use" *Jonrnal of I.P.E.*, Vol. XVIII, No. 11, November 1939, p. 433).

(2) *Double mandrel method* (c.f. Figs. 2 and 16). In this method a carefully centred mandrel (of special design) on the main spindle is compared with another mandrel of exactly the same diameter on the opposite machine component, *e.g.* turret head, overhanging arm, etc., by means of a clock indicator fixed to some suitable base moving in a fixed plane, such as on a lathe carriage. The first mandrel must have a large flange sometimes with a suitable, accurately fitting spigot welded to the actual cylindrical testing part (Fig. 17a). These spigots and spindle noses in general are not standardised—they may be cylindrical (as in the Ward machine), tapered (as in the Jones and Lamson) or a combination of both (*e.g.*, in the Lodge and Shipley). Twelve further variations, taken from current practice, are shown in Fig. 20. Thus a very large number of special mandrels must be available for inspecting machine tools by this method by the user.

There are further disadvantages. Since the mandrels are opposite each other, and should be 12 in. in length to fulfil the test conditions, there must be over 24 in. clear between the main spindle face and the turret head itself; the fact that the mandrels may have different natural sags must also be allowed for. The main spindle mandrel

must be checked for eccentricity and both mandrels arranged so that their axes must coincide with their axes of rotation in the planes perpendicular to those in which readings are taken.

Finally the flange and spigot must be a good central fit if they are used. But the main spindle spigot dimensions may vary anywhere

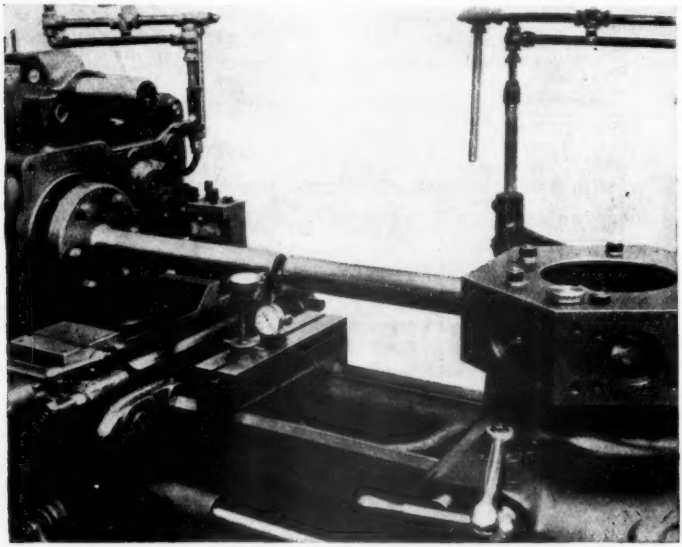
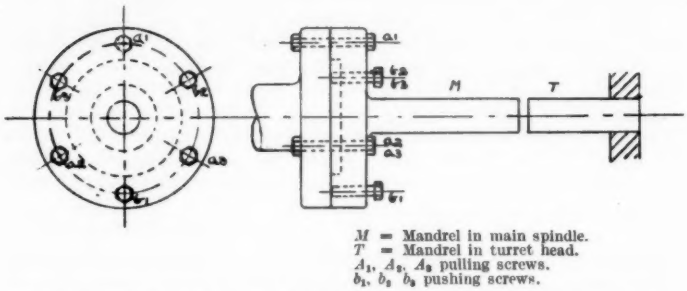


Fig. 16.—Turret lathe, headstock, and turret hole, tested by double mandrel method.



M = Mandrel in main spindle.
T = Mandrel in turret head.
A_1, A_2, A_3 pulling screws.
b_1, b_2 b_3 pushing screws.

Fig. 17a.—Ordinary design of flanged adjustable mandrel in the headstock.

within the permissible tolerance. Hence the flange on the test mandrel must be made to suit a spigot made to the high limit size and will not be a sufficiently precise fit on a spigot made to the low limit. To avoid this, the mandrel must be made with six bolts as shown in Fig. 17 to allow final adjustment till its axis coincides with the axis of rotation. This is not an easy operation.

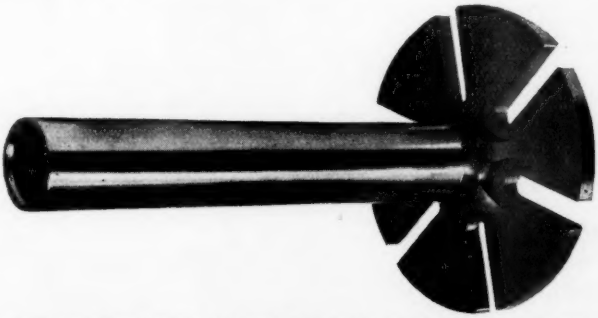
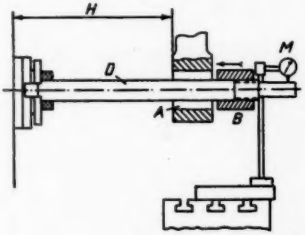


Fig. 17b.—Improved design of flanged adjustable mandrel with hollow cylinder (Whitehouse).

The flanged hollow mandrel (Fig. 17b) designed by H. Whitehouse, Birmingham, is a great improvement to the older style (according to Fig. 17a). It is hollow, avoiding unnecessary sag, and it uses six slots which allow to vary the distance of the bolts and even to forego the spigot.



A = Bore to be tested.
B = Slip bushing.
D = Test mandrel.
M = Dial guage.
H = Distance of overarm from spindle nose

Fig. 18.—Principle of slip bushing test.

(3) *Slip bushing method* (Fig. 18 and 19). This method is commonly used on milling machines, taking an arbor, known to be accurate and in good condition as the test mandrel. The test is made by taking clock readings in the position shown in Fig. 18, then moving the bushing into the overhanging arm, and taking readings again,

thus determining the amount by which the arbor is strained from its free position (Fig. 19).

This method has the advantages that it can be done quickly, and that the clock indicator is stationary, but it has several dis-

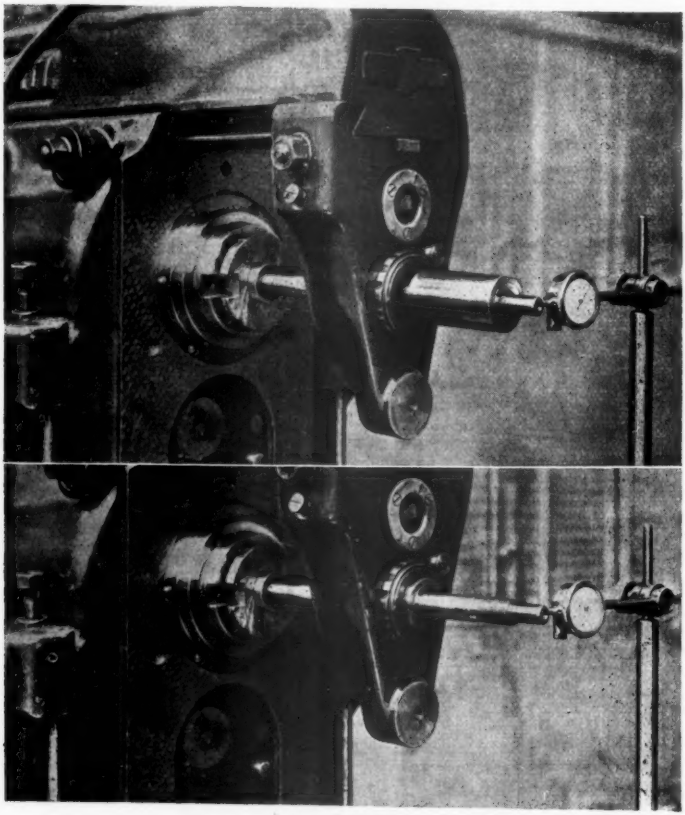


Fig. 19.—Execution of slip bushing test.
Top*—Bushing outside of arm.** ***Bottom **Bushing slipped-in.**

advantages also. The arbor must be very accurate and run true, since it has to be turned during the test. Any errors in the main bearing affect the result, as in the swing-around method. Thus these errors must be measured beforehand (finding the mean posi-

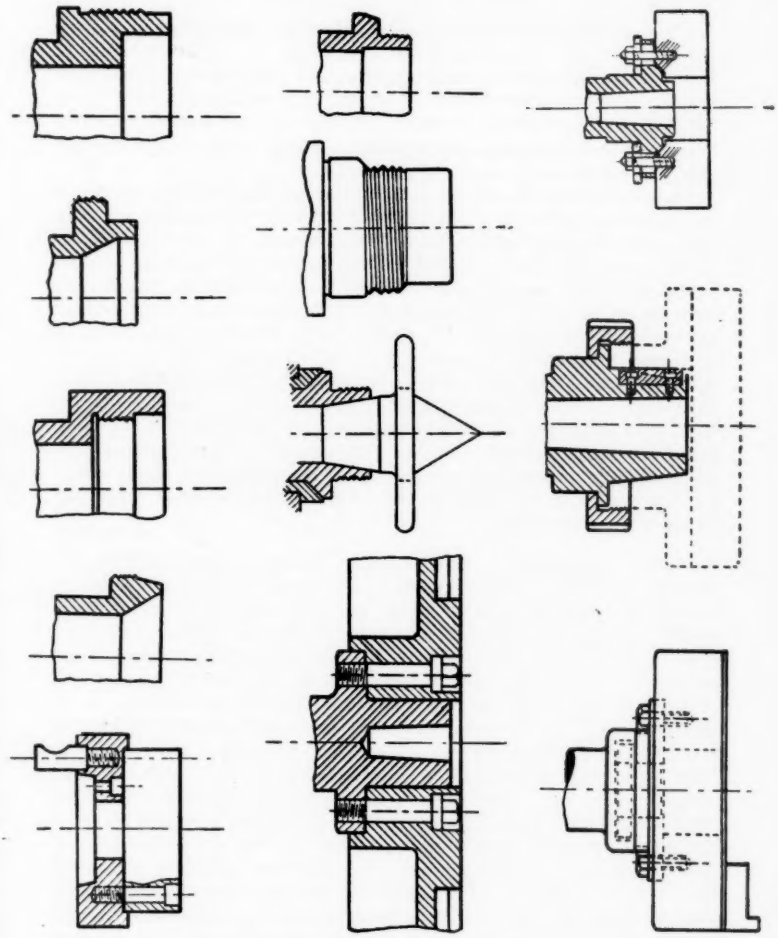


Fig. 20.—Design of twelve different modern spindle noses of lathes and turret lathes.

tion) so that they may be allowed for in the actual test. Errors between the axes of the spindle and arbor are due to (*a*) incorrect taper, (*b*) eccentricity, (*c*) lack of truth, (*d*) deviation from the cylindrical.

The arbor itself is generally long relative to its diameter, so that the natural sag is (comparatively) large. This sag could be diminished if a hollow mandrel were used, but this is a special instrument which cannot be represented by an ordinary milling machine arbor. Such arbors are usually grooved to take up the cutter, therefore the clock indicator must be applied to the short cylindrical part at the outer end.

Similar objections arise from the use of the bushing itself. It must be fully concentric and cylindrical internally and externally, and must be a good sliding fit on the arbor and in the bracket.

Also cast-iron bushings are heavy (between 2 and 4 lb., depending on the machine), and bronze bushings are still heavier, so that the increase in the sag of the mandrel, shown above to be considerable, must be allowed for. Only if all the above conditions are complied with can this method be accepted as being sufficiently accurate.

Tools of this difficult kind may be useful in the hands of the maker, but they are, in the majority of cases, not so in the hands of the user, because a great variety of non-standardised mandrels, brackets and bushings and main spindle noses demand such a great amount of tools that the method could only be recommended if the whole industry were to standardise the internal and external diameters of all these components.

SOME NOTES ON TIME STUDY RELATED TO BULK AND LINE PRODUCTION

By P. H. Lee, M.I.P.E., A.M.C.T.

Introduction.

AS a result of the intensification of production for war purposes, it may be that more attention has been given to the question of line or bulk production than has been the case hitherto, and some firms will be trying to introduce such methods for the first time. It is to time study engineers thus engaged that these notes are offered in the hope that they may assist, if only in a small way, to accelerate the war effort. In any particular case the method employed for obtaining " time values " is not of paramount importance provided that it gives reasonably satisfactory results. It should be remembered that finality is never reached, and one must be prepared to profit by experience. At the present time one should not be afraid to experiment, and it may well be that some new methods will emerge as a result of the war. Moreover, all the care and thought which is being put into this matter now should be of value to industry after the war, when new difficulties may arise.

Definition.

Line production may be described as that method of production in which the workers do not complete an article, or perform complete operations. They each perform only a part of the work so that a group of workers is needed to complete the operation. When quantities are sufficiently large to justify it they may perform only an element, but in practice it is more usual for each operative to do a number of elements, which we may call a sub-operation. Generally it means that materials and parts are fed to the line at one end, work is done on them at the various stages, and a finished article is delivered at the other end. Some parts may be assembled off the line and fed in at the appropriate stage.

It is a logical extension of the idea of specialised production. In the past men fed and clothed themselves, whereas nowadays there are probably very few who can do this successfully. Early developments were that one became a tailor, another a baker, and so on. This idea has been further developed so that a tailor may make only a part of a suit, and a baker may specialise in producing a certain type of pastry. When this is carried to a logical conclusion it may mean that a man is set to "tighten up nuts A and B with the left and right hands respectively."

Advantages.

The application of line production under normal conditions will give a reduced labour cost as compared with that obtained when each worker completes an article alone. This follows as a result of the specialisation which is possible with the consequent increase of output per operative. By this means it is possible to employ less skilled workers, if such a course is necessary, as each has less to learn and less to remember than is the case when each one has to complete an article unaided.

Juniors may be employed on certain of the sub-operations where the work is not of a heavy character. The less intelligent type of worker can be more readily used by this means than is the case when it is necessary for the operative to perform a number of operations. The quality of the work tends to be better as each worker becomes very skilled in the performance of the particular part of the work for which he or she is employed. There are those who would argue the reverse, but in practice it is generally found that the work is definitely of a higher standard, which in these days of keen competition is no mean factor, as it may mean the difference between a repeat order and the loss of the work. This should be fairly obvious, but there are a number of people who find it hard to believe for some reason or another.

Not the least important feature of line production is that it is possible to obtain the maximum output from the plant and floor space available with the resultant reduction in on-cost charges.

Disadvantages.

One objection to this method of production is the undoubted monotony. Where women are extensively employed this objection is not serious, as women by nature do not seem to mind monotony to the same extent as men. As a matter of fact they often prefer a job of work which calls for a minimum of concentration.

There are considerable difficulties to be overcome in organising a line production scheme, not least of which is " absenteeism." In order to cope with this trouble it is a wise plan to have a number of operatives trained to do more than one part of the operation in order that they may be moved from point to point as is found necessary, so that the line is not held up. It is important that the seriousness of delay is fully apprehended as time lost is not necessarily that of only one worker. A number will probably be affected, and if this point is not carefully watched it will nullify the advantages to a certain extent.

The Initiation of a Line for Bulk Production.

The time study engineer plays a vital part in the organisation of a line. It will be necessary for him to arrive at the proper time

factor so that the line may be correctly synchronised. If data is available from previous studies taken of the operation when performed by workers working individually it will be a great help, provided the engineer knows how to make use of it. This calls for the application of sound common sense. Assuming, then, that it is necessary to start up a line for some product which has previously been made by workers individually, it will first of all be necessary to study each element carefully, and it should be noted that some of the elements will not be speeded up to the same extent as others. Those elements which require the greatest dexterity will probably give the greatest reduction of time when done in line, whereas those which are short and simple will be found to be reduced least. It is impossible to dogmatise about this point, as some astonishing results are often obtained. This is particularly noticeable if one is not familiar with this type of production.

As a preliminary experiment a reduction of 25% can be tried on the longer elements. This figure is, of necessity, an arbitrary one, and may need to be adjusted as experience is gained of the actual working of the line. The question of adjustment is one which requires care, as the group will tend to work at the speed of the slowest operative. One worker may have a little more than his or her share to do at the beginning, and this will also tend to slow the line down. Observation will soon show this, and it can be dealt with quickly.

There is often some controlling factor in the line such as a machine or a group of machines, which govern the flow of work along the line. In this case it will be necessary to organise the work in such a way as to secure the maximum output from the machines, and to arrange the operations to suit.

In setting values for work done on a line, it may be found that the total will not divide up into exactly equal parts, and as a matter of fact it would be very remarkable if this were to occur. When this difficulty arises it may be overcome by arranging groups of more than one operative for those operations which cause difficulty in this way.

The following simple example will serve to illustrate this point. Assume that an operation is divided into four sub-operations, the values for which are—

Sub-operation No.	1	...	...	...	...	2.46	minutes.
,, ,,	2	...	...	...	...	5.25	,,
,, ,,	3	...	...	...	...	2.30	,,
,, ,,	4	...	...	...	...	2.60	,,

In this example it will be seen that it is necessary to have two workers on sub-operation No. 2 in order to even out the time, and

to prevent a hold-up at that stage. The "feed time," which is the highest time required to complete a sub-operation, is in this case 2.625 minutes, i.e., $\frac{5.25}{2}$. This means that one article should leave the line every 2.625 minutes. The operatives engaged on this work would be paid as a group, and the value would be five times the feed time plus allowances for relaxation and delay. In the example given this is 5×2.625, which equals 13.125 minutes, and if we take the allowances as $12\frac{1}{2}\%$ the value becomes 14.765 minutes each or 1,477 minutes per 100.

There is a loss due to imperfect synchronisation which is obtained by adding the sub-operation values together, and subtracting the figure obtained from the net value. In this example the loss is equal to 13.125 minus 12.610, i.e. 0.515 minutes. This difference is one of 4%, which is about twice as high as it should be, and is due to the small group chosen as an example. In setting values for operations performed on a line such as this, the loss due to imperfect synchronisation should be kept down to approximately 2%. One should not be satisfied until this figure is reduced to a minimum, as this loss is one which has to be subtracted from the saving made by the change to this method of production.

When a large number of articles are required it will be possible to split the operation into smaller sub-operations, in which case it will be easier to reduce the differences to a minimum. At the same time it will not be possible to eliminate this loss altogether, as that would infer perfect organisation, which is, of course, more or less impossible when the human element is involved.

A great deal may be done to secure satisfactory synchronisation by rearranging the operation. It is surprising how few operations must be performed in the order in which they are normally done. Most of them can be adjusted, even only slightly, and advantage can be taken of this in order to obtain smooth working of the line.

Further Examples.

In order to make the method of selecting values for line production from data obtained by study of workers who completed an article quite clear, the following example is given :—

OPERATION—ASSEMBLE PART "A."

Study No.	*Value in minutes each.*
1010	2.13 minutes at 100—2.130
1011	2.42 „ „ 90—2.178
1012	2.58 „ „ 85—2.193
1013	1.76 „ „ 110—1.936
1014	3.15 „ „ 70—2.205
1015	1.55 „ „ 120—1.860
1016	2.72 „ „ 80—2.176

It will be seen that there are seven readings, which if arranged in ascending order are—

1.860, 1.936, 2.130, 2.176, 2.178, 2.193, and 2.205.

These values were obtained from operatives working alone, and if the normal method of selection is used the value would be 2.176 minutes. When the workers are specialising they will easily perform the operation in times approximating to, or better than, the smallest value given by the table. In view of this fact the first reading of 1.860 minutes may be taken without the risk of being too optimistic. As a matter of fact, when operatives have had an opportunity of becoming accustomed to the work they will probably do much better than this.

As has already been mentioned, those elements which are very short and which require no skill will not show the same reductions. For example, an element such as " pick up part B " which may take, say, 0.010 minutes, will not usually show much saving when done in line production. At the same time it may be well worth while arranging for a special receptacle to hold the parts in order to facilitate production.

When No Previous Data is Available.

So far the notes have been confined to the case of a line arrangement when information is available regarding the manufacture of the article in the ordinary way by operatives working individually. When this information is not to hand it will be necessary to base the initial " lay-out " on estimated figures.

If the use of machinery is involved to any extent the figures will have to be carefully worked out, as errors may be expensive, and difficult to rectify later. In making these estimates the operations should be split up into the smallest possible elements, as it is only by doing this most carefully that reasonably reliable figures can be obtained. A list of the elements should be made up with the times alongside so that the total can be divided up into suitable groups.

When considering these figures it is necessary to take into account the following factors :—

(1) The total quantity ordered.
(2) The rate of delivery asked for by the customer.
(3) The number of operatives required.
(4) The space required for efficient production.
(5) Any local peculiarities which may influence the arrangements.

In order to give an example of this type it will be necessary to assume certain figures, and for this purpose the following may be used :—

The total quantity ordered 500,000.
Rate of delivery required, say 5,000 per day.
Hours worked per day by the operatives, $9\frac{1}{2}$.
Assume the total time to be twenty minutes each.

From this it will be seen that the number of workers required is given by the calculation $\frac{5{,}000 \times 20}{570}$ which equals approximately 176. Space will be needed to allow this number of operatives to work efficiently. In arranging this, the size of the article will, of course, have to be taken into account. The amount of space required for each sub-operation will not necessarily be the same as some of the parts may be much smaller than others.

The following operations and times are hypothetical, but they will serve to illustrate how this kind of problem can be attacked.

Sub-operation.	*Time in minutes.*	*No. of operators.*
Prepare part "A"	1.0	9
Assemble part "A"	3.5	31
Sew part "A"	1.5	13
Prepare part "B"	0.5	4
Assemble part "B"	3.5	31
Finish part "B"	1.5	13
Assemble "A" and "B" ...	4.5	40
Sew assembly	1.5	13
Finish assembly	1.5	13
Stamp and pack	1.0	9
TOTALS	20.0	176

From these figures it will be seen that 26 sewing machines will be required in order to give the rate of output asked for by the customer.

The values were made as simple as possible for easy working, but this did not prevent fractions in the calculation of the number of operatives required for each sub-operation. Where this occured the figure has been given to the nearest whole number. For example, the number of operatives required for sub-operation, "Prepare part A" worked out at 8.8, but 9 is given as being the nearest whole number. When the workers become thoroughly proficient it may be possible to reduce this number to eight. This applies to all groups since the calculations have been based on an estimate. In dealing with quantities of this size the question of fractions of an operative should not present serious difficulty.

In the example given, the quantity required would be completed in approximately 100 days, or twenty weeks of five working days.

In practice it may be considered that an order which could be completed in twenty weeks would not justify the organisation of a

line. This question is one that calls for careful thought, and all the relevant factors must be considered. The chief point is, of course, will production by the line method give a smaller labour cost than would be the case if the article were made in the ordinary way? Apart from the question of cost, there is the point that it is a simpler matter to train new workers for work on the line than to teach them to make the complete article. This is an important consideration when it is necessary to introduce a number of new operatives, and it is desired that the maximum output should be obtained quickly. There are instances where it takes an operative about two months to learn to complete an article satisfactorily, whereas about two weeks are sufficient for him to learn to perform a sub-operation successfully. This represents a saving of six weeks, which is quite important, when it is remembered that the cost of training new workers may be considerable.

In the example given the operatives should be paid separately, and not as a group as in the previous example. The number of workers engaged on the line justifies the additional clerical work necessary to do this, and it will encourage the workers to give of their best. A small proportion of them may be capable of doing 30 to 50% more than the remainder, and it would be a pity to restrict these workers to a lower output. Where this occurs it will be necessary to reduce the group. For example, if the operatives engaged on the first sub-operation are capable of giving an output equivalent to 120% of that which is asked, the number would be reduced from nine to seven or eight in order to allow them to earn more than the average. If the capabilities of the workers are known beforehand it will be possible to take care of this point from the start, and if the workers are machinists it may save the cost of one or two machines.

It may be argued that it is unfair to take advantage of these operatives who are capable of giving above the standard effort, but it is impossible to obtain a group of workers who all work at exactly the same speed, and it is reasonable to allow all of them to give their best effort. Certain advantages accrue to those who are known to be good, since they are retained if it becomes necessary to lay workers off for any reason, and they are usually given work which allows them to earn a higher pay than the standard.

Example of a Conveyor Belt.

If the type of article and the quantity required justify the erection of a conveyor belt the calculations involved are no more difficult than those already dealt with. The preliminary calculations should be carefully done so that unnecessary expense can be avoided. Urgency may indicate the necessity for the use of a belt even if it does not give the cheapest possible production, although this will

usually be obtained, but the question of recovering the cost of the installation must be taken into account.

For the purposes of these notes a simple example will serve. Again the values and the operations are hypothetical.

Assume the following figures :—

Production required	...	...	...	1,000 per day.
Value (total time)	...	...	...	42.8 minutes each.
Hours worked per day	...	...	...	9½ to 570 minutes.

Then the number of operatives required is given by the calculation

$$\frac{42{,}800}{570} = 75.$$

Sub-operation.	*Time in minutes.*	*No. of operatives.*
Prepare part "A"	1.7	3
Assemble part "A"	2.3	4
Machine part "A"	2.9	5
Prepare part "B"	1.7	3
Assemble part "B"	3.5	6
Machine part "B"	1.0	2
Finish part "B"	1.7	3
Prepare part "C"	2.3	4
Assemble part "C"	4.0	7
Finish part "C"	2.3	4
Assemble "A" and "B" ...	5.7	10
Machine assembly	1.7	3
Assemble "C" to "A" and "B"	3.5	6
Machine assembly	2.3	4
Finish assembly	4.5	8
Stamp and pack	1.7	3
TOTALS	42.8	75

It will be seen that the highest feed time is given for those sub-operations where the value is 3.5 minutes and the number of workers is six, and is equal to $\frac{3.5}{6} = 0.583$ minutes. The total time value is equal to 0.583×75, which is 43.7 minutes.

The difference between this time and the total of the sub-operation times is 0.9 minutes and represents a loss due to imperfect synchronisation of 2.1%, which is quite reasonable. In connection with this point it should be noticed that the total number of finished parts delivered at the end of the belt will be equal to $\frac{570}{0.583}$ which is 978 and not the 1,000 with which we started, but this loss can easily be made up without extending the operatives to any extent.

It will be necessary to add suitable allowances to the value obtained to take care of fatigue and any breaks which may be given.

Fatigue can be lessened by introducing breaks in the working periods. Such intervals should be of about fifteen minutes duration, and should be given about two-thirds of the way through each period to secure maximum efficiency in view of the probable monotonous character of the work.

If we give two such intervals of fifteen minutes each in this example the time lost will represent 5.6%., i.e. $\frac{30}{570-30}$. In addition to this allowance it will be necessary to give an allowance to take care of fatigue, and if we make this 7% we have a total of 12½% approximately. This has to be added to the value of 43.7 minutes already obtained, which makes it 48.2 minutes each.

If we assume a space of 6 ft. between each working place, the belt speed will have to be such as to transport the parts 6 ft. in 0.583 minutes, which is equal to 10.29 ft. per minute.

Conclusion.

It will be appreciated that it has not been possible to give figures relating to actual examples, but the ones given should make the principles clear. One difficulty which often arises is that the time for some sub-operation is such that a fraction of an operative is required. When this particular trouble occurs it may be overcome by grouping two sub-operations together or by re-arranging the operation.

The question of storage has not been dealt with, but such racks as are necessary may be fitted over the belt or the work benches, provided that they do not interfere with the lighting.

Time study engineers should be familiar with the principles of line production even if they have not had practical experience of the operation of a line, and these notes may be of use to such engineers.

THE EFFECTS OF DILUTION OF LABOUR IN THE WORKSHOP UNDER PRESENT-DAY CONDITIONS

*By J. H. Mills, Stud.I.P.E.**

THE initial consideration when introducing diluted labour into the workshop under present conditions is its effect on speeding up production. At the same time the quality of the product must not suffer, as all forms of armaments whether aircraft, tanks, or ammunition must be manufactured to extremely fine limits, and placing unskilled operatives on such work is an entirely different proposition from introducing them into, say, cheap household goods industries.

Hence the problem presents itself as to whether the effect of dilution on output will be beneficial or not. This can be answered definitely ; the introduction of diluted labour will meet the present requirements of production, provided that the necessary precautions are taken in the manufacturing technique employed.

The first essential is that every job on which diluted labour is employed must be tooled up with absolute accuracy, and the tools must be incapable of being used incorrectly. Fitting work will be superseded wherever possible by machining or press operations, as it is far easier to train an operator to use a machine tool than, say, a file with accuracy. Large assemblies will have to be split up into light sub-assemblies for youths and girls. Planning must be revised to split up operations to suit the capabilities of the operators available. Many actual processes will be revised, due to both dilution and quantities required. For instance, sheet metal panels on aircraft, previously beaten or wheeled are now produced on drop hammers or rubber bolster presses. Large diameter pipes are pressed in two sections and welded together instead of being bent by highly skilled coppersmiths.

Full use will be made of milling, drilling, welding and other jigs and fixtures, and where possible the operator should be able to use them without having to think. This especially applies to female labour, as these operators have a great capacity for repetitive work without becoming bored.

Diluted labour in the inspection department presents no great

* This was adjudged to be the best Essay at the 1940 Graduateship Examination.

snags on simple viewing, provided that complete sets of foolproof gauges and templates are provided, and master templates and gauges kept for reference. When materials are to be tested, semi-skilled labour is suitable for taking readings on instruments such as the Firth Hardometer.

If these main conditions are observed, the primary desired effect of dilution, i.e., increased production, will be attained, but in turn this will create its own effects.

Firstly, the increase in the cost of tooling for a project will be great (often about 400% of normal), but with the demand for large quantities this will be spread out so as to make the cost of tooling, per component, an extremely low figure, so that this effect on outlay is not serious. In spite of precautions a slight increase in the amount of scrapped work will doubtless occur, due to the unskilled element, but this will not be large enough to be a major effect. Overhead charges will increase, as unskilled labour is rarely cheap labour. The snag about so much tooling is that the number of toolroom operatives will be insufficient. Dilution is impracticable here, but skilled fitters and turners, whose jobs are to be done by " dilutees " may be promoted to the toolroom. There will also be a demand for such workers in machine tool factories and to a certain extent in drawing offices. Thus we can foresee an influx of unskilled workers into factories producing armaments and similar commodities, and a movement of large numbers of skilled workers to tool work, whilst some remain to become chargehands and foremen. This movement must be reasonably controlled, and must be fairly gradual to prevent draining any particular branch of industry.

So far only the productive effects have been considered, but the human effects are of equal importance, and the difficulties which arise must be promptly overcome or dilution will become a curse and defeat its own ends.

Firstly, the effects on the skilled workers already employed in factories. The co-operation of trade unions regarding dilution has been obtained quite satisfactorily for neither the obstacles presented nor the price appear to be as great as they might have been. However, it is only natural for a certain amount of discontent to arise when skilled operators see semi or unskilled workers taking on jobs which they have worked on for several years, perhaps having developed them from experimental to production stages (often with highly gratifying results from a bonus point of view). In such cases a skilled man thinks himself indispensable on that job, and to see a " dilutee " taking it on is as iron in his soul. When possible this must be prevented by keeping the new operators in a separate section, and transferring the requisite jobs straight over there. Thus much natural pride is spared, and as the job is probably replanned to suit the newcomers' ability, the change is soon forgotten.

However, when a keen skilled man feels that he is only doing a semi-skilled job he aspires to something better, and this will militate towards the movement of personnel previously described. At the moment no great discontent has arisen, having been largely avoided by good wages (by which is meant wages plus bonus), and it appears that in future wages for skilled workers are bound to increase, though on account of taxation effective wages will not vary much. A good effect of dilution is that with the wider experience which skilled men will now obtain, in toolrooms, machine tool factories or drawing offices, they will be much more efficient in their old jobs if they return to them.

The effect on " dilutees " of entering the workshop should be carefully considered. Frequently the wages they will in time obtain (for after a year or so a " dilutee " is very valuable) will be in excess of wages they previously obtained. This will raise their standard of living and some will no doubt wish to remain in industry. The keener ones will attend technical classes to improve their prospects, and industry will gain from dilution, as amongst the thousands engaged some latent talent will appear, which will be useful even when the present conditions no longer obtain. Keen and able workers should not be held back merely because they came into the factory under a dilution scheme.

The most recurrent and noticeable problems occurring through labour dilution have been mentioned, but beneath the surface the main source of discontent in all classes of labour is their probable position after the war. Skilled workers see in the newcomers a potential danger to themselves and their families. This is a probable effect of dilution and must be avoided ; skilled men who have been apprenticed must never be made to suffer for it, and ill-timed advantage should not be taken of the present situation to attempt to undermine legitimate trade union representation. On the other hand, if tackled properly, work could also always be found for the present " dilutees."

Dilution in the last war is often blamed for the present shortage of skilled labour. Parents were discouraged from putting their sons in industry when they saw so many shops employing unskilled labour at low wages. To prevent a recurrence of this, it is likely that the whole principle of apprenticeship will be overhauled, making wages and training during apprenticeship and prospects after apprenticeship much more attractive and secure. Although this is a very big step, it has been successfully accomplished abroad (e.g., at Junkers' and Heinkels', the German aircraft firms) and in a few cases at home.

Scientific selection of personnel will develop through dilution. Hitherto it has been the practice in most engineering firms to engage new operators by impressions gained by the employment

manager or even foremen, coupled with the candidates' past experience. This becomes a more complex problem when the applicants have no previous experience and where a large number have to be interviewed each day. Psychological tests will become more widely used and may save time and money by selecting the right operator for a certain operation. Concurrently job specification will be brought up to date. In addition, the welfare department will develop as it should find good scope for its activities in guiding the newcomers to engineering.

Hence we see that the desired effect of dilution will be realised, but that the repercussions of its dependent effects may substantially affect the whole country for many years, unless carefully handled. On the other hand, this country will have an enormous quantity of trained producers and if use were always found for them the future prosperity of the country would not be a matter of mere conjecture and hazard.

THE EFFICIENT UTILISATION OF LABOUR UNDER WAR CONDITIONS

Mr. B. JENKINS, Grad.I.P.E., has sent to the Institution a letter (December 18, 1940) putting forward proposals for the organisation of a Mobile Squad of Engineering Workers. Points from Mr. Jenkins' letter are :—

" My scheme is to set up a Voluntary Mobile Squad of Workers, from which men can be drawn for work in their own trade in any part of the country. It often happens in the larger works that more employees are taken on during a busy spell, and are retained during the slacker periods ready for the next busy spell, so that part of the time these employees are not working to full capacity. The employer does this to safeguard himself, as if he were to release his men during a slack period he would have difficulty in getting additional labour when required. The result is that firms employ enough people to deal with the maximum volume of work they expect to get, and a large proportion of their time is not fully occupied. This applies particularly to the more highly skilled trades.

" If my scheme were to be adopted for the period of the war, and men were encouraged to enrol on the Register for duty anywhere in the country, a pool would be created from which an employer could draw as and when he required labour, and to which he could apply when he wished to deplete his staff. In this way an employer could balance up his staff to suit the amount of work in hand. In other words, the pool would be used as a reservoir to reduce the fluctuations of demand to supply to a minimum.

" The plan would be that men at present working for Firm A should be considered to be employed at that firm for the duration of hostilities, and could only be transferred to Firm B with the consent of the men themselves and their employer, and on the understanding that they would be returned to Firm A when required. It may happen that a man would be transferred to several different firms before eventually returning to his " parent " firm, but all transfers would take place through the central pool with the consent of all concerned, and subject to various regulations which would be framed in collaboration with the various trade unions concerned, who, I believe, would be willing to co-operate."